UNPUBLISHED PRELIMINARY DATA

STATUS REPORT

Period 1 April, 1963 to 31 March, 1964

NASA Grant NsG-39-60

Entitled

# CAVITATION EROSION PHENOMENA

BY

Frederick G. Hammitt

Laboratory for Fluid Flow and Heat Transport Phenomena
Department of Nuclear Engineering
The University of Michigan
Ann Arbor, Michigan

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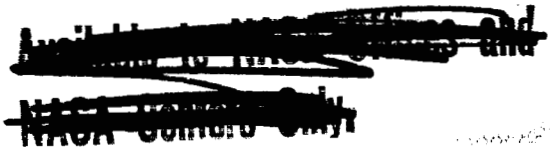
# I. INTRODUCTION

The University of Michigan cavitation-erosion research program being conducted under NASA Grant NsG-39-60 is approximately on the schedule described in the Status Report for the period 1 April, 1962 to 31 March, 1963 from the viewpoint of expended funds. However, it is anticipated that the time period for the completion of the presently foreseen work will be somewhat extended. Consequently it is not planned to submit a proposal for additional funding at this time. However, it may become desirable to do so at a later date, perhaps for the next fiscal year.

During this report period the work under the NASA grant has been strongly complimented by an NSF grant with roughly parallel objectives. Also a portion of the work previously considered as part of the NASA grant has been supported during this report period by contracts from Pratt and Whitney Aircraft and Atomics International.



# II. OVERALL UNIVERSITY OF MICHIGAN CAVITATION-EROSION PROGRAM

## A. General Objectives

The program objective is to assist the overall national cavitation research effort in obtaining the necessary level of understanding and data to allow optimized designs of turbomachinery and other fluid-flow components from the viewpoints of cavitation performance and damage. Special emphasis in the present project is to be placed upon the high-temperature liquid-metal area as applied to SNAP power plants, etc.

To attain this objective, an experimental program, supplemented by theoretical analyses to broaden the applicability of the experimental results, using fluids, materials, and flow parameters selected to cover the range of interest, but avoiding those combinations of fluid and temperature conditions impractical to attain with the relatively modest facility levels available, is required. The development of the facilities required at the University of Michigan has been essentially completed during this report period, and a substantial portion of the data taken. It appears that the present funding is adequate to complete the test program presently visualized. It is believed that the resultant data will be highly significant in determining the interrelations between fluid, material, and flow parameters, and cavitation damage.

Final prototype tests of components in the actual environment will no doubt be desirable, although these are extremely

expensive and limited in generality. Such tests are not a reasonable part of the University of Michigan program. However, experimentation of reduced scope under conditions approaching those of prototype interest may be desirable and practical. The choice of such critical experiments will be limited in number and cost by the more basic studies under more easily controllable conditions which are part of the present program.

B. Facilities Available

The cavitation facilities here available developed under the NASA and NSF grants have already been described in the literature;* and hence will be merely summarized:

1. Automated High-Speed Water Tunnel - Capable of velocities up to about 225 ft/sec. with water, with temperature up to about 300°F. Twelve damage specimens can be tested simultaneously in four parallel loops. Alternatively one loop can be used for cavitation performance tests with either the cylindrical venturis used in most previous tests, or a special two-dimensional venturi with adjustable throat opening. Deaereation and deionization capability is included.
2. Liquid Metal Tunnel - Presently in use with mercury at temperatures up to about 600°F. Maximum velocity with mercury is about 65 ft./sec.; more with a lighter fluid. General design of loop is suitable for 1000°F to 1200°F range.

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* "Cavitation Damage and Performance Research Facilities", F. G. Hammitt, ASME Fluids Engineering Division Conference, Phila., Pa., May, 1964, Symposium on Cavitation Research Facilities and Techniques, pp. 175-184.

3. Vibratory Cavitation Facility - Capable of producing a total amplitude of about 2 mils at 20 KC in fluids ranging in density up to mercury, and at temperatures up to about 1500°F, pressures at temperature to about 50 psig.

In addition a facility for the study of high-velocity impact with liquid drops or solid particles is under development using a small-calibre rifle as the propelling mechanism.

## III. PROGRESS DURING PRESENT REPORT PERIOD

### A. Progress on Sub-Projects (Itemized in Status Report, period 1 April, 1962 to 31 March, 1963, Section III)

1. Damage Testing in Water Facility - A total of approximately 15,000 specimen-hours was accrued during the period. (About 3000 had been forecast for the period). The materials used include some chosen primarily for their technological interest and others primarily for the combination of mechanical properties which they possess. Some materials, of course, satisfy both criterions. In the first and/or third category are:

i) Type 302 Stainless Steel
ii) 1010 Carbon Steel
iii) Refractory alloys
iv) Aluminum alloys
v) Plexiglas

and in the second category:

i) Pure copper (three heat-treat conditions used)
ii) Brass (70/30) (Three heat-treat conditions used)
iii) Copper-Nickel (Three heat-treat conditions used)
iv) Pure nickel (Three heat-treat conditions used)

The above materials (twelve in all since there are four materials with three heat-treat conditions for each) were chosen so that the effects of a substantial variation of a single property, as grain size, tensile strength, strain energy to failure, etc., could be examined while other properties remained

constant. All the materials are highly resistent to corrosion in water, so that the damage should be largely of mechanical origin. The coppers and brasses have all been tested to 100 hours (adopted as a standard duration) for various velocities and degrees of cavitation. The copper-nickel series is in progress and the pure nickel yet to start although specimens have been fabricated and heat-treated. The necessary mechanical property tests on all the applicable materials is substantially complete.

Tests are continuing on the various materials listed for the first and/or third category. The longest duration so far attained is 300 hours on two sets of nine specimens.

For all damage specimens pit sizes and numbers are tabulated (as long as pits remain distinct), weight losses* are measured, photomicrographs* taken of interesting pit configurations, and sections of pitted areas from specimens for which the cavitation tests have been completed are made.

2. Damage Testing in Mercury Facility - A total of approximately 1400 specimen hours has been accrued during the period. The test program has emphasized the following aspects, utilizing 302 stainless steel, carbon steel, Cb - 1Zr alloy, two tantulum refractory alloys, and plexiglas:

a. Continued tests of "conventional" specimens to evaluate the effects of long duration. Longest duration set has now attained 800 hours.

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* A digital read-out precision balance and a metallographic camera have been added to the laboratory equipment during this report period.

b. Tests of specimens held under varying tensile loads during the tests to evaluate in a preliminary fashion the effects of prestressing, and to determine the effects upon gross mechanical properties of a known amount of cavitation damage (since the specimen design was such that stress-strain curves could be run at the conclusion of the tests).

c. Tests of refractory alloys to determine their relative resistence to cavitation damage at room temperature (parallel tests conducted in water facility).

d. Development of pin-type specimen (held across stream in cavitating diffusor portion of venturi) as an accelerated cavitation device, and also to allow a more complete range of prestressed tests (as b. above where high degrees of precompression also are included).

e. Tests with "dry" vs. "wet" mercury. It was found that the mercury as used in all previous tests included a trace of water - perhaps order of 100 to 1000 ppm. When the water was almost entirely removed by heating it was found that the damage rate was reduced by an order of magnitude and the mercury "wet" the stainless steel test specimens much more effectively, so that it had to be driven off under heat and vacuum to attain a true weight measurement. It is felt that this considerable reduction in damage by the removal of a small quantity of water may hold a key to possible methods of damage inhibition. A similar motivation applies to the precompression tests already mentioned.

f. Damage tests with mercury at 500°F on stainless steel primarily to evaluate effect of higher mercury vapor pressure. (Considerable increase in damage rate for "dry" mercury from room temperature to 500°F was found).

The necessary fabrication, preparation, and examination, of specimens has continued. Tested specimens are all pit-counted and weighed at intermediate steps, and photomicrographs and cross-sections taken where desirable.

3. Miscellaneous Tests and Developments in Tunnel Facilities

a. Installation and Operation of High-Temperature Components - A 50 hour damage test at 500°F has been completed as well as several other shorter runs at temperatures up to about 550°F. Although it had been intended to replace the mercury with lead-bismuth alloy during this report period, it is now felt that operation with high-temperature mercury is more useful at present.

b. Completion of runs with irradiated test specimens of stainless steel and carbon steel in mercury, and of subsequent data reduction. Report issued and paper delivered on subject to ANS.*

c. Additional measurements of void fraction in cavitating flow regimes in both water and mercury. Further tests in water are contemplated to complete the series. However, an interim report and ANS and also ASME papers were presented.

d. Fabrication and initial testing of two-dimensional

* Delivered in June, 1964, subsequent to report period.

plexiglas venturi with throat opening adjustable between 1/8" and 3/4" has been completed. Use is being made of this venturi for high-speed motion picture studies of bubble growth and collapse in a known flow regime. High-speed picture capability of this laboratory has been increased during the report period by procurement of

i) Edgerton-Germeshausen and Grier Model 50 High-Speed Stroboscope capable of producing 6000 repetitive flashes per second of about 1.2 microsecond duration, synchronized with a Fastax camera,

ii) Fastax (8 mm) high-speed motion picture camera capable of about 14,000 frames/sec.,

iii) Courtney-Pratt lenticular lens high-speed motion picture camera capable of about 100,000 frames/sec.

iv) Miscellaneous items (including a Dynafax high-speed motion picture camera capable of about 25,000 frames/sec.) which may be borrowed if required from other University of Michigan Laboratories.

Continuous use of high-speed motion picture and still cameras has been made during report period for studies of bubble growth and collapse both in mercury and water.

e. Theoretical analyses of single-bubble growth and collapse considering all "real fluid" variables as a Ph.D. thesis, which should be completed before end of calendar year.

f. Scale effects studies in water and mercury cavitating venturis. Experiments to determine cavitation number for various degrees of cavitation as a function of velocity, size of venturi, gas content ( water and mercury*), other impurity effects as for example water contamination in mercury*, temperature, and prepressurization history. This work, with special emphasis on the effects of entrained gas, has been primarily supported under a contract with Atomics International, and is being carried out in part, as a Ph.D. thesis.

g. Detailed measurements of pressure along faces of cavitation damage specimens as a function of velocity, venturi configuration (number of specimens and orientation), degree of cavitation, etc. This work is being carried out as a portion of a Ph.D. thesis.

h. Development of vibratory facility (NSF grant, portion of a Ph.D. thesis). Check-out of the unit at low temperature, calibration and measurement of amplitude, development of electronic amplitude read-out device, development of suitable specimen design, development and partial fabrication of holder-vessel assembly for

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* Special devices, believed patentable, for the determination of gas and water trace contents in mercury have been developed.

high temperature**, procurement and check-out of suitable furnace complete. It is expected to test identical materials (as far as possible) as used in the tunnel facilities under the same fluid and temperature conditions in the vibratory facility thus achieving a valid comparison between the two types of test. Finally, tests up to 1500°F in lead-bismuth (a fluid quite similar to mercury, but capable of high-temperature operation without prohibitive vapor pressure problems) with stainless steel, carbon steel, and various refractories (and perhaps other materials) are planned.

i. Publication and issuance of numerous reports, papers, articles, etc. (17 separate items as listed under V - Project Publications).

j. Preliminary development of device to study high-velocity impacts of solid and liquid particles, with particular attention to the possible analogy to cavitation damage. Pits created in all these fashions will be examined in detail to determine their similarities, and the dependence of their shape on rate of leading, etc. (Ph.D. thesis).

## IV. Anticipated Continuation of Work under NASA Grant

The continuation of those portions of the work which it is anticipated will be supported under the NASA grant are summarized in this section.

### A. Damage Testing in Water Facility

** Key to this design is a special seal-holder arrangement, believed patentable, between vessel and vibrating horn.

1. Completion of tests to 100 hours duration on copper-nickel, pure nickel, aluminum (three alloys), and plexiglas considering different velocities and cavitation conditions.
2. Continued long-duration testing of stainless steel, carbon steel, and perhaps other specialized materials as loop time becomes available.
3. Completion of mechanical property tests on all tested materials.
4. Correlation of data in terms of mean depths of penetration and its time derivative (rate), with various mechanical property groupings.
5. Completion of pressure measurements around specimens in various degrees of cavitation and velocities.
6. If possible, explore effect of gas content and perhaps temperature on damage rates.
7. If possible, explore effects of different test specimen geometries and resultant flow patterns. It is felt that the imposition of strong vorticity on the otherwise more or less translatory flow in the venturi would closely model the most damaging type of flow encountered in turbomachinery, but under controlled and known pressure and velocity conditions.
8. Attempt to develop models correlating damage with fluid and material properties and degree of cavitation and other flow parameters.

B. <u>Damage Testing in Mercury Facility</u>

1. Continuation of long-duration tests in "wet-cold" mercury.
2. Further exploration of effect of "dry-cold" vs. "wet-cold" mercury.
3. Further exploration of effect of "dry-hot" vs. "dry-cold".
4. Exploration of damage effects with pin-type specimen as an accelerated cavitation device and also a necessary component for further prestressed tests.
5. Continuation of prestressed tests after 4. above. It is felt that items 2., 3., and 5. may lead to methods of partially inhibiting cavitation damage in a given flow pattern.
6. As items 3. through 8. of Section A above.

## V. Project Publications

03424-8-T, "Detailed Investigation of Cavitation Pitting Characteristics from Cavitating Venturi Tests", ORA Technical Report No. 03424-8-T, Laboratory for Fluid Flow and Heat Transfer Phenomena, Univ. of Mich., F. G. Hammitt and L. L. Barinka (April, 1963).

03424-9-T, "Cavitation Damage in Mercury and Water in a Cavitating Venturi and Other Components", F. G. Hammitt, L. L. Barinka, V. A. Biss, R. D. Ivany, R. D. Pehlke, M. J. Robinson, and C. A. Siebert, ORA Technical Report No. 03425-9-T, Laboratory for Fluid Flow and Heat Transfer Phenomena, Univ. of Mich. (Sept., 1963).

03424-10-T, "Cavitation Damage in Mercury by Radio-tracer Analysis", W. Smith, J. M. Nieto, and F. G. Hammitt, ORA Technical Report No . 03424-10-T, Laboratory for Fluid Flow and Heat Transfer Phenomena, Univ. of Michigan, (Oct., 1963).

03424-11-T, "Determination of Cavitation Conditions from Density Profiles of Mercury in a Venturi", I. B. Lauchlan, F. G. Hammitt, R. D. Ivany, and M. J. Robinson, ORA Technical Report No. 03424-11-T, Laboratory for Fluid Flow and Heat Transfer Phenomena, Univ. of Mich. (Oct., 1963).

03424-12-T, "Cavitation Damage and Performance Research Facilities", F. G. Hammitt, ORA Technical Report No. 03424-12-T, Laboratory for Fluid Flow and Heat Transfer Phenomena, Univ. of Mich., (Nov., 1963).

03424-13-T, "Cavitation Damage Performance of Stressed Specimens", L. L. Barinka, F. G. Hammitt, M. J. Robinson, R. D. Pehlke, and C. A. Siebert, ORA Technical Report No. 03424-13-T, Laboratory for Fluid Flow and Heat Transfer Phenomena, Univ. of Michigan, (Nov., 1963)

03424-19-I, "Analysis of Hardness Indenter Pit Profiles", F. G. Hammitt, L. L. Barinka, R. J. McHugh, and M. J. Robinson, ORA Internal Report No. 03425-19-I, Laboratory for Fluid Flow and Heat Transfer Phenomena, Univ. of Michigan, (April, 1963).

03424-20-I, "On Transient Loading Effects in Cavitation Pitting", F. G. Hammitt, L. L. Barinka, R. J. McHugh, and M. J. Robinson, ORA Internal Report No. 03424-20-I, Laboratory for Fluid Flow and Heat Transfer Phenomena, University of Michigan, (July, 1963).

03424-21-I, "Initial Phases of Damage to Test Specimens in a Cavitating Venturi as Affected by Fluid and Material Properties and Degree of Cavitation", F. G. Hammitt, L. L. Barinka, M. J. Robinson, R. D. Pehlke, and C. A. Siebert, ORA Internal Report No. 03424-21-I, Laboratory for Fluid Flow and Heat Transfer Phenomena, University of Michigan, (December, 1963).

03424-22-I, "Void Fraction Measurements in Cavitating Mercury", F. G. Hammitt, Willy Smith, I. B. Lauchlan, R. D. Ivany and M. J. Robinson, ORA Internal Report No. 03424-22-I, Laboratory for Fluid Flow and Heat Transfer Phenomena, University of Michigan, (Feb., 1964). Also presented ANS Annual Meeting, Philadelphia, June, 1964.

03424-23-I, "Cavitation Damage Measurements by Radio-Tracer Analysis", F. G. Hammitt, Willy Smith, J. M. Nieto and M. J. Robinson, ORA Internal Report No. 03424-23-I, Laboratory for Fluid Flow and Heat Transfer Phenomena, University of Mich. (Feb., 1964). Also presented ANS 1964 Annual Meeting, Philadelphia, June, 1964.

"Void Fraction Measurements in a Cavitating Venturi", W. Smith, G. L. Atkinson, F. G. Hammitt, ASME Paper No. 63-AHGT-19, ASME Hydraulics Division Meeting, Spring, 1963, Also Trans. ASME, J. Basic Eng., June, 1964, pp. 265-274.

Discussion by F. G. Hammitt on "Cavitation Damage to Centrifugal Pump Impellers during Operation with Liquid Metals and Molten Salt at 1050-1400° F", by R. G. Smith, J. H. DeVan, and A. G. Grindell, Trans. ASME, J. Basic Engr., Sept., 1963 pp. 335-336.

Discussion by F. G. Hammitt on "Visual Cavitation Studies of Mixed Flow Pump Impellers", by G. M. Wood, Trans. ASME, J. Basic Engr., March, 1963, p. 28.

Discussion by F. G. Hammitt on "A Unified Theory of Cavitation Damage", by A. Thiruvengadam, Trans. ASME, J. Basic Engr., Sept., 1963, pp. 373-375.

Discussion by F. G. Hammitt on "Experimental Investigations of Incipient and Desinent Cavitation", by A. F. Lehman and J. O. Young, Trans. ASME, J. Basic Engr., June, 1964, p. 281.

Discussion by F. G. Hammitt on "A Visual and Photographic Study of the Inception of Vaporization in Adiabatic Flow", by E. P. Mikol and J. C. Dudley, Trans. ASME, J. Basic. Engr., June, 1964, p. 262.